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Report: Carbon Cycling in High-Latitude Ecosystems

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The carbon-rich soils and peatlands of high-latitude ecosystems could substantially influence atmospheric concentrations of CO_2 and CH_4 in a changing climate. Currently, cold, often waterlogged conditions retard decomposition, and release of carbon back to the atmosphere may be further slowed by physical protection of organic matter in permafrost. As a result, many northern ecosystems accumulate carbon over time (Billings et al., 1982; Poole and Miller, 1982), and although such rates of accumulation are low, thousands of years of development have left Arctic ecosystems with an extremely high soil carbon content; Schlesinger's (1984) average value of 20.4 kg C/m^2 leads to a global estimate of 163×10^{15} g C.

All GCM simulations of a doubled CO_2 climate predict the greatest warming to occur in the polar regions (Dickinson, 1986; Mitchell, 1989). Given the extensive northern carbon pools and the strong sensitivity of decomposition processes to temperature, even a slight warming of the soil could dramatically alter the carbon balance of Arctic ecosystems. If warming accelerates rates of decomposition more than rates of primary production, a sizeable additional accumulation of CO_2 in the atmosphere could occur. Furthermore, CH_4 produced in anaerobic soils and peatlands of the Arctic already composes a good percentage of the global efflux (Cicerone and Oremlund, 1988); if northern soils become warmer and wetter as a whole, CH_4 emissions could dramatically rise. A robust understanding of the primary controls of carbon fluxes in Arctic ecosystems is critical.

As a framework for a systematic examination of these controls, we discussed a conceptual model of regional-scale Arctic carbon

turnover, including CH_4 production, proposed by E. Holland, and based upon an extension of the Century soil organic matter model (Parton et al., 1987, this volume). The details of Century will not be repeated here; rather, we will restrict our discussion to the specific modeling challenges posed by Arctic ecosystems.

Biophysical Model

Both soil temperature and soil moisture status are critical determinants of carbon dynamics in any ecosystem. Some unique features of the Arctic physical environment complicate the prediction of these variables:

- Permafrost, or permanently frozen subsurface soil, underlies much of the Arctic. It has a significant effect on regional hydrology by providing an impermeable barrier to vertical infiltration. Changes in permafrost will alter the size of the active carbon pool, regional hydrology, and perhaps topography through uneven settling. The extent to which the permafrost layer may change in a warmer climate is not well known, but recent evidence from oil wells in northern Alaska suggests a distinct warming trend in the permafrost over the 20th century.
- Snow, being a very effective insulator, can dramatically affect the soil thermal regime. In addition, snowmelt is a dominant source of water to Arctic ecosystems.
- Freeze/thaw processes in the soil are important to the regional hydrology (frozen soil is impermeable) and to the soil thermal regime due to delays at 0°C resulting from the energy requirements of a change in phase. The timing of the spring thaw is crucial, because it occurs when available sunlight is high (May-June). An earlier thaw would greatly enhance ecosystem productivity, and a deeper thaw in permafrost regions would thicken the active decomposition layer.

Due to high spatial variability of these factors in the Arctic, we believe a fairly comprehensive biophysical model of the soil environment that provides input to the carbon turnover model will be necessary for regional-scale simulations (Figure 1). The present conceptual structure of this model contains four distinct layers (Figure 2): unsaturated peat or soil at the surface; saturated peat or soil; deep, unfrozen, saturated mineral soil or extensively decomposed peat; and permafrost. Changes in the extent of the top two layers (that is, changes in the water table) may occur on time scales of days to weeks, while significant changes in permafrost are only likely to occur on decadal time scales.

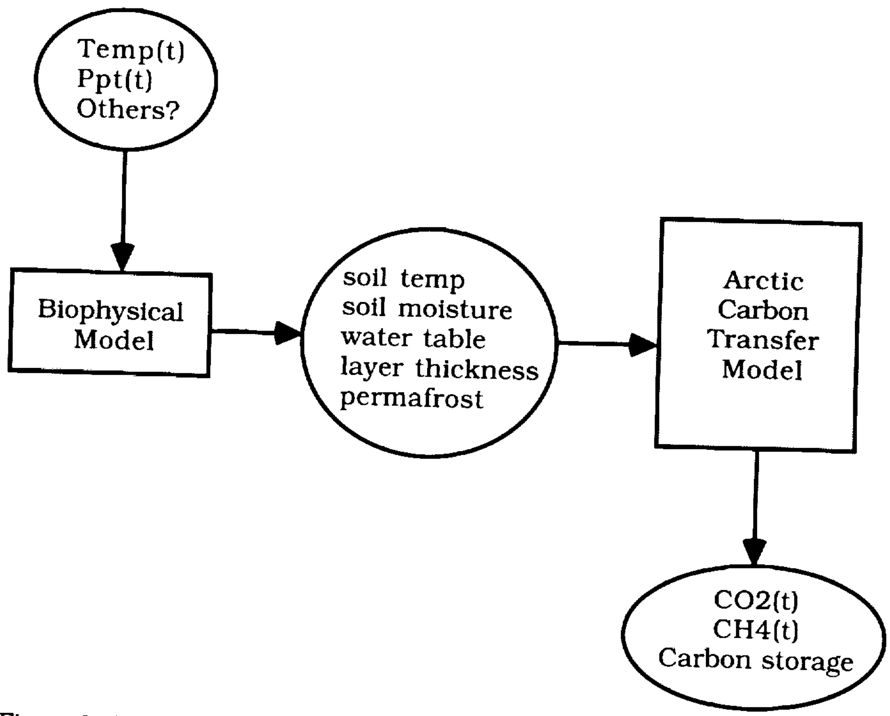

Figure 1. A diagram of the coupling of the Arctic carbon cycling model with the soil biophysical model. Inputs are climate variables, intermediate results are soil temperature and moisture profiles, and final outputs are CO_2 and CH_4 flux time series and the annual change in soil carbon storage.

Model inputs include the thermal and hydraulic properties of the surface vegetation and soil layers, and a parameterization of lateral surface water movement. The model will be driven by (at minimum) air temperature and precipitation, and will determine the temperature profile of each layer, the thickness of the aerobic vs. saturated layers, seasonal depth of thaw, and changes in permafrost. As well, the model will need to determine snow depth, extent of snow cover, and timing of snowmelt.

Carbon Turnover Model

Development of a good biophysical model is just one of a number of modeling challenges posed by Arctic ecosystems. While fluxes of carbon between the atmosphere and ecosystems are low, the stocks of available substrate in the soils are enormous. As a result, the initial response of Arctic systems to climate change will not be dramatic, but the cumulative effects and feedbacks to the climate system on longer time scales are potentially extreme. The most critical unknowns in predicting these dynamics concern the responses of

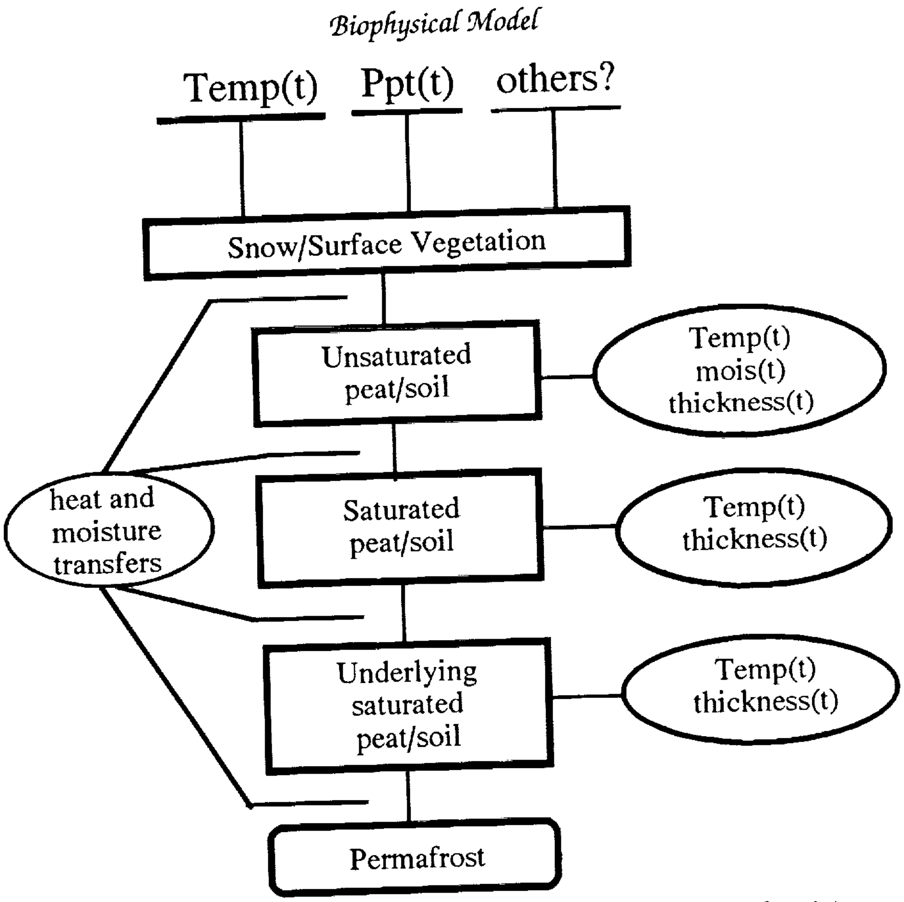

Figure 2. Schematic of biophysical model of soil heat transfer and moisture flux. Climate variables drive the model, and the output is the physical state of the modeled soil layers.

decomposition vs. production to changes in temperature and moisture. Whether any ecosystem produces a net release or uptake of carbon to or from the atmosphere in a given year depends on the ratio of primary production to decomposition. In the Arctic, this is a quotient of two relatively small numbers, so that the potential for a sizeable change in this ratio is high.

If inputs and effluxes of carbón varied in a similar fashion in response to climate-related perturbations, there would be less cause for concern, but most current evidence suggests that this is not the case. In a recent review of soil respiration (Raich and Schlesinger, in preparation), the authors point out that the vast majority of studies show soil CO_2 efflux to be related to temperature in an exponential fashion, with a mean Q_{10} of 2.4. Nadelhoffer et al. (1991) found essentially no change in soil respiration with temperatures between

2° and 10°C, but a large and rapid increase above 10°. Temperature effects on production of Arctic vegetation are poorly understood, but most existing evidence suggests a more linear relationship. If this is the case, warming in the northern latitudes could actually result in carbon accumulation in the soils, thus creating a negative feedback to further warming. The accumulation of carbon in tundra during warmer, interglacial periods lends some credence to this hypothesis. This potential sink of carbon could only exist, however, over a limited range; if temperatures increase enough to push the exponentially responding decomposition processes beyond those of production, the balance could shift to a net efflux, thereby generating a positive feedback leading to even higher temperatures (Townsend et al., in preparation). The actual responses of decomposition and production in Arctic environments to temperature changes and the current rates of these processes must be identified before accurate predictions of future dynamics are possible.

Temperature represents only one of many factors that can influence carbon balance. A similar analysis may be applied to moisture, whose controls and likely changes in a doubled-CO_2 climate are even less well understood. In general, both decomposition and production often increase in an exponential fashion with greater moisture availability over certain ranges, but excess moisture will render soils anaerobic and retard rates of production and decomposition. Due to the nonlinear nature of these processes, the responses and current conditions need to be worked out.

These challenges, however, do not preclude the design and preliminary application of a simulation model for carbon dynamics. Figure 3 is a diagram of the model's general structure, with total ecosystem carbon being divided into three vegetation compartments and three soil compartments. At present, Century calculates production as a function of temperature and moisture; we believe Arctic vegetation may also require an irradiance parameter. On shorter time scales and in the tundra, woody biomass should have little impact on the climate-induced responses; thus it is represented as an isolated pool. Both root and aboveground biomass create residue organic matter, which in turn feeds into the available soil carbon pool. The third soil pool, permafrost, is completely recalcitrant, but can feed into the other soil pools upon thawing. The details of this exchange will be determined by the biophysical model outlined earlier. Estimates of allocation between above- and below-ground material can be made from a variety of studies (cf. Chapin et al., 1986a, 1986b; Chapin and Shaver, 1988), as can estimates of lignin:N ratios. Since most of the tundra is highly organic, soil texture will not play as important a role as it does in other ecosystems. Signifi-

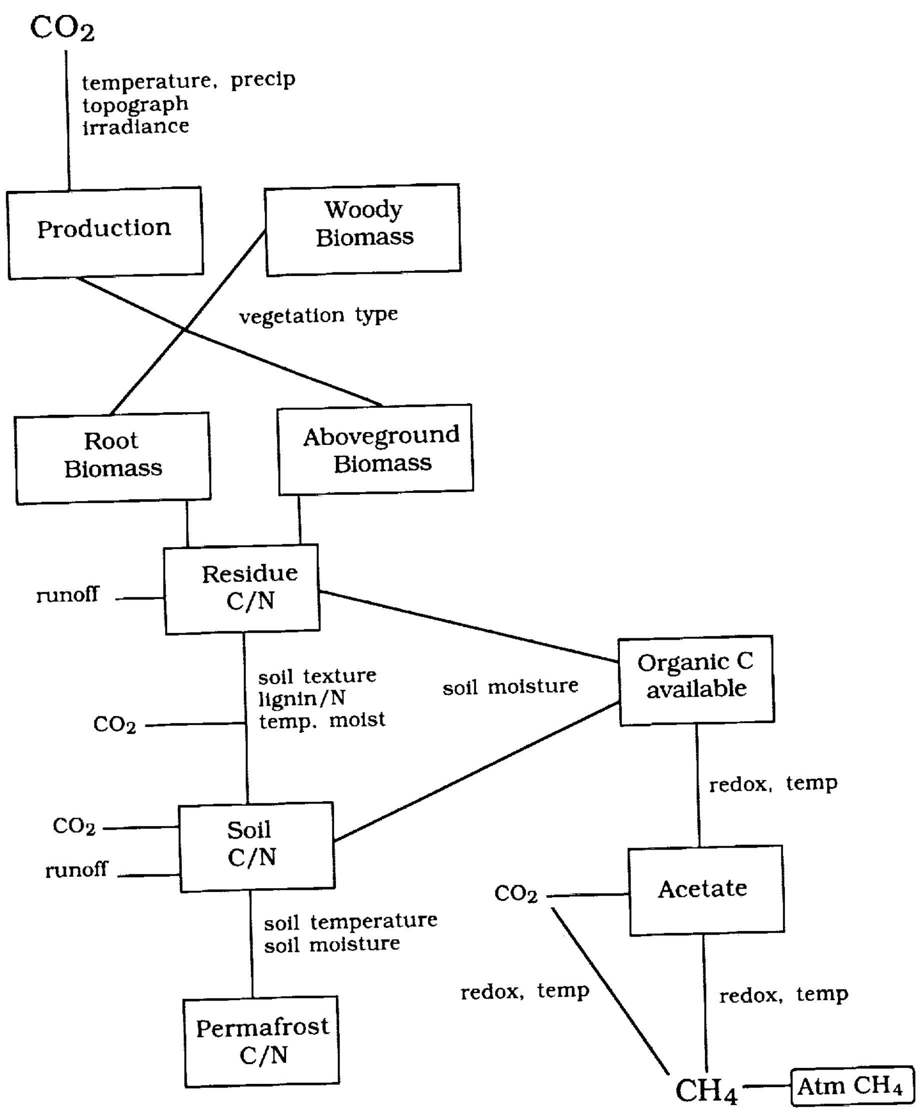

Figure 3. Conceptual model diagram for soil carbon, CO_2, and CH_4 cycling in Arctic ecosystems.

cant transport of organic acids through peat layers and into streams and groundwater could occur.

Waterlogged conditions may slow decomposition and the subsequent release of CO_2, but they do allow methanogenesis to occur; a warmer, wetter Arctic could also result in a positive feedback to further warming via accentuated CH_4 release from anaerobic peatlands and bogs. Work is currently under way to expand the Century struc-

ture to simulate CH_4 fluxes. Briefly, carbon in the soil and residue pools may become available for methanogenesis when anaerobic conditions arise. The proportion of this carbon that is converted to CH_4 is a function of soil temperature and redox status. Redox itself is a function of moisture and microbial activity, so that microbial utilization of oxygen in the previous time step will affect the redox state of the present time step. Oxidation of CH_4 produced to CO_2 is also determined by redox state, as well as by the speed at which CH_4 can escape to the atmosphere. A greater percentage of CH_4 produced will be released in vegetated areas, because plants provide effective conduits through the water/soil layer (Conrad, 1989; Schutz et al., 1989a, 1989b). Where vegetation does not supersede standing water, transport from source areas to the atmosphere is slower, relying on diffusion, ebullition, and wind-generated turbulence for escape. For this reason, vegetated and open-water areas should be treated differently in calculations of CH_4 flux. Finally, CH_4 is allowed to enter the soil/water environment from the atmosphere as a function of the concentration gradient. There is some suggestion (Steudler et al., 1989; Mosier et al., 1991) that CH_4 uptake by soils may be closely tied to N status, so that it may eventually be possible to tie this flux to the mineralization rates calculated by the central model.

Regional-Scale Modeling

Spatial heterogeneity can be extreme in Arctic regions (Miller, 1982). Therefore, extension of the model to regional scales will be challenging. As there is some evidence that Arctic vegetation can be tightly correlated with water status, some knowledge of topography (e.g., via digital elevation models) might also allow estimates of the vegetation parameters. This relationship is by no means certain; Miller (1982) states that vegetation zones in central Alaska are largely determined by nutrient availability rather than water status.

The best approach to spatial extrapolation of the local model may be that of King et al. (1989), which uses probability distributions and Monte Carlo sampling techniques to generate expected values throughout large regions to provide inputs to the ABISKO II (Bunnel and Scoullar, 1975) model. Estimates of the probability functions for the model inputs might be possible from a combination of regional vegetation maps, AVHRR data, and thematic mapper data bases. Using a probability function approach to calculate expected values in space may be critical in the Arctic, as many of the important dynamics respond in nonlinear fashion, and conventional averaging-in-space approaches could produce greatly erroneous results.

Critical Field Measurements

Complete data sets needed for model parameterization and validation are scarce, but some information is available from sites in Minnesota, Alaska, Scandinavia, and the Hudson's Bay region of Canada. Efforts to study carbon dynamics in northern latitudes are increasing (e.g., Svensson and Rosswall, 1984; Chapin et al., 1986a, 1986b; Sebacher et al., 1986; Crill et al., 1988; Whalen and Reeburgh, 1988; Nadelhoffer et al., 1991; and the National Aeronautics and Space Administration's Global Tropospheric Experiment/Arctic Boundary Layer–3 experiments). NASA, the National Environmental Research Centre (United Kingdom), and the Canadian Institute for Research in Atmospheric Chemistry are currently planning large-scale field campaigns in the boreal and tundra regions during the next few years. Nevertheless, we will have to know much more to test and direct regional-scale simulation models. A list of needed information follows:

- Production, decomposition, and CO_2 and CH_4 flux measurements coupled with soil moisture and temperature over at least a growing season, including freeze and thaw periods, and preferably for a full year in sites that span the general range of Arctic ecosystem types. This is the most critically needed information.
- Time series of winter snowpack, snowfall, air temperature, and the effects of topography on snowpack. Some such data exist (e.g., Woo et al., 1983).
- Depth profiles of organic carbon to the permafrost layer throughout the Arctic. Again, limited data are available, and Doolittle et al. (1990) suggest that ground-penetrating radar may provide a rapid and accurate means for determining the depth to frozen soil and thus the thickness of the active layer.
- Carbon-13, carbon-14, and deuterium isotope values for gas fluxes. The deuterium isotopic ratio can be used to determine whether methane was produced from acetate or carbon dioxide; the carbon isotopes allow differentiation among various types of substrate.
- Redox profiles (pH, pe) for various soil moisture conditions. One set of such data is available from northern Alaska.
- Soil texture (where applicable) and soil hydraulic and thermal properties for both organic and mineral soils.
- Root-shoot ratios and the lignin:N ratios for each vegetation component in different Arctic regions.

- Dissolved organic carbon and particulate organic carbon in rivers and streams. We need to determine how significant these are in the overall carbon balance.

- Atmospheric deposition rates of N and S compounds. Key questions here are whether N inputs fertilize these systems and whether S inputs provide significant alternative electron acceptors for microbial reduction.

Some Additional Questions

The model we outline here does not address the issue of methane hydrates or clathrates, that is, CH_4 trapped in ice lattices in permafrost and in the marine sediments of continental shelves. Kvenvolden (1988) reviews estimates of their extent (ranging from 1.7 to 4000 teratons of CH_4) and gives pressure-temperature phase diagrams for hydrate stability. If these hydrates are destabilized, the CH_4 can then be released. We believe that a separate modeling effort is needed to assess the time scale of hydrate destabilization by climate change and the subsequent movement of CH_4 to the land or sea surface.

The atmospheric CH_4 record reconstructed from ice-core data (Chappellaz et al., 1990; Rasmussen and Khalil, 1984; Craig and Chou, 1982) raises two questions:

- The high-latitude peatlands began forming about 9000 to 6000 years ago (Heinselman, 1975). Since these peatlands are a major natural source of CH_4 to the atmosphere, is there evidence in the ice-core record of the appearance and growth of such a significant source of methane?

- Is there evidence in the Vostok core CH_4 record of hydrate destabilization, and, if not, how sensitive are hydrate formations to climate perturbations?

References

Billings, W.D., J.O. Luken, D.A. Mortensen, and K.M. Petersen. 1982. Arctic tundra: A source or sink for atmospheric carbon dioxide in a changing environment? *Oecologia* 53, 7–11.

Bunnell, F.L., and K.A. Scoullar. 1975. ABISKO II: A computer simulation model of carbon flux in tundra ecosystems. In *Structure and Function of Tundra Ecosystems* (T. Rosswall and O.W. Heal, eds.), Ecological Bulletin 20, Swedish Natural Science Research Council, Stockholm, 425–448.

Chapin, F.S. III, J.D. McKendrick, and D.A. Johnson. 1986a. Seasonal changes in carbon fractions in Alaskan tundra plants of differing growth form: Implications for herbivory. *Journal of Ecology 74*, 707–732.

Chapin, F.S. III, G.R. Shaver, and R.A. Kedrowski. 1986b. Environmental controls over carbon, nitrogen, and phosphorus fractions in *Eriophorum vaginatum* in Alaskan tussock tundra. *Journal of Ecology 74*, 167–195.

Chapin, F.S. III, and G.R. Shaver. 1988. Differences in carbon and nutrient fractions among Arctic growth forms. *Oecologia 77*, 506–514.

Chappellaz, J., J. Barnola, D. Raynaud, Y. Korotkevich, and C. Lorius. 1990. Ice-core record of atmospheric methane over the past 160,000 years. *Nature 345*, 127–131.

Cicerone, R., and R. Oremlund. 1988. Biogeochemical aspects of atmospheric methane. *Global Biogeochemical Cycles 2*, 299–327.

Conrad, R. 1989. Control of methane production in terrestrial ecosystems. In *Exchange of Trace Gases between Terrestrial Ecosystems and the Atmosphere* (M.O. Andreae and D.S. Schimel, eds), Dahlem Conference, John Wiley and Sons, Chichester, England, 39–58.

Craig, H. and C. Chou. 1982. Methane: The record in polar ice cores. *Geophysical Research Letters 9*, 1221–1224.

Crill, P., K. Bartlett, R. Harriss, E. Gorham, E. Verry, D. Sebacher, L. Madzar, and W. Sanner. 1988. Methane flux from Minnesota peatlands. *Global Biogeochemical Cycles 2*, 371–384.

Dickinson, R.E., A. Henderson-Sellers, P.J. Kennedy, and M.F. Wilson. 1986. *Biosphere-Atmosphere Transfer Scheme for the NCAR Community Climate Model*. Technical Note NCAR/TN-275+STR, National Center for Atmospheric Research, Boulder, Colorado, 69 pp.

Doolittle, J.A., M.A. Hardisky, and M.F. Gross. 1990. A ground-penetrating radar study of active layer thicknesses in areas of moist sedge and wet sedge tundra near Bethel, Alaska, U.S.A. *Arctic and Alpine Research 22(2)*, 175–182.

Heinselman, M. 1975. Boreal peatlands in relation to environment. In *Coupling of Land and Water Ecosystems* (A. Hasler, ed.), Ecological Studies No. 10, Springer-Verlag, New York.

King, A.W., R.V. O'Neill, and D.L. DeAngelis. 1989. Using ecosystem models to predict regional CO_2 exchange between the atmosphere and the terrestrial biosphere. *Global Biogeochemical Cycles 3(4)*, 337–361.

Kvenvolden, K. 1988. Methane hydrates and global climate. *Global Biogeochemical Cycles 2*, 221–230.

Miller, P.C. 1982. Environmental and vegetational variation across a snow accumulation area in montane tundra in central Alaska. *Holocene Ecology 5*, 85–98.

Mitchell, J.F.B. 1989. The greenhouse effect and climate change. *Review of Geophysics 24*, 115–139.

Mosier, A., D. Schimel, D. Valentine, K. Bronson, and W. Parton. 1991. Methane and nitrous oxide fluxes in native, fertilized and cultivated grasslands. *Nature 350*, 330–332.

Nadelhoffer, K.J., A.E. Giblin, G.R. Shaver, and J.A. Laundre. 1991. Effects of temperature and substrate quality on element mineralization in six arctic soils. *Ecology 72(1)*, 242–253.

Parton, W.J., D.S. Schimel, C.V. Cole, and D. Ojima. 1987. Analysis of factors controlling soil organic levels of grasslands in the Great Plains. *Soil Science Society of America Journal 51*, 1173–1179.

Poole, D.K., and P.C. Miller. 1982. Carbon dioxide flux from three Arctic tundra types in north-central Alaska, U.S.A. *Arctic and Alpine Research 14(1)*, 27–32.

Raich, S.W., and W.Y. Schlesinger. Global CO_2 flux in soil respiration and its relationship to climate (in preparation).

Rasmussen, R., and M.A.K. Khalil. 1984. Atmospheric methane in the recent and ancient atmospheres: Concentrations, trends, and interhemispheric gradient. *Journal of Geophysical Research D7*, 11599–11605.

Schlesinger, W.H. 1984. Soil organic matter: A source of atmospheric carbon dioxide. In *The Role of Terrestrial Vegetation in the Global Carbon Cycle* (G.M. Woodwell, ed.), SCOPE 23, John Wiley and Sons, Chichester, England, 111–127.

Schutz, H., A. Holzapfel-Pschorn, R. Conrad, H. Rennenberg, and W. Seiler. 1989a. A 3-year continuous record on the influence of daytime, season, and fertilizer treatment on methane emission rates from an Italian rice paddy. *Journal of Geophysical Research D13*, 16405–16416.

Schutz, H., W. Seiler, and R. Conrad. 1989b. Processes involved in formation and emission of methane in rice paddies. *Biogeochemistry 7*, 33–53.

Sebacher, D., R. Harriss, K. Bartlett, S. Sebacher, and S. Grice. 1986. Atmospheric methane sources: Alaskan tundra bogs, and alpine fen, and a subarctic boreal marsh. *Tellus 3B*, 1–10.

Stauffer, B., E. Lochbronner, H. Oeschger, and J. Schwander. 1988. Methane concentration in the glacial atmosphere was only half that of the preindustrial Holocene. *Nature 332*, 812–814.

Steudler, P.A., R.D. Bowden, J.M. Melillo, and J.D. Aber. 1989. Influence of nitrogen fertilization on methane uptake in temperate forest soils. *Nature 341*, 314–316.

Svensson, B., and T. Rosswall. 1984. In situ methane production from acid peat in plant communities with different moisture regimes in a subarctic mire. *Oikos 43*, 341–350.

Townsend, A., P.V.M. Vitousek, and E.A. Holland. Tropical soils dominate the short term carbon cycle feedbacks to atmospheric CO_2 (in preparation).

Whalen, S., and W. Reeburgh. 1988. A methane flux time series for tundra environments. *Global Biogeochemical Cycles 2*, 399–409.

Woo, M., R. Heron, P. Marsh, and P. Steer. 1983. Comparison of weather station snowfall with snow accumulations in high arctic basins. *Atmosphere–Ocean 21*, 312–325.